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"Keyhole" Coronary Artery Bypass Surgery

Rodney J. Landreneau, M.D.* Michael J. Mack, M.D.,† James A. Magovern, M.D.,*
Tea A. Acuff, M.D.,† Daniel H. Benckart, M.D.,* Tamara A. Sakert, R.N.,*
Lynda S. Fetterman, R.N.,* and Bartley P. Griffith, M.D.‡

From the Division of Cardiothoracic Surgery, Allegheny General Hospital Campus, Alleghany University of the Health Sciences, Medical College of Pennsylvania/Hahnemann University, Pittsburgh, Pennsylvania; the Division of Cardiothoracic Surgery,† Medical City Hospital, Dallas, Texas; and the Division of Cardiothoracic Surgery, University of Pittsburgh, Pittsburgh, Pennsylvania*

Objective
The objective of this study was to identify the utility of "keyhole" thoracotomy approaches to single-vessel coronary artery bypass surgery.

Summary Background Data
Although minimally invasive surgery is efficacious in a wide variety of surgical disciplines, it has been slow to emerge in cardiac surgery. Among 49 selected patients, the authors have used a mini-anterior keyhole thoracotomy (6 cm in length) combined with complete dissection of the internal mammary artery (IMA) pedicle under thoracoscopic guidance or directly through the keyhole incision to accomplish IMA coronary artery bypass grafting (CABG) to the left anterior descending (LAD) coronary artery circulation or to the right coronary artery (RCA).

Methods
Keyhole CABG was accomplished in 46 of 49 patients in which this approach was attempted. All patients had significant (> 70%) obstruction of a dominant coronary artery that had failed or that was inappropriate for endovascular catheter treatment (percutaneous transluminal coronary angioplasty or stenting). Forty-four of the 49 patients had proximal LAD and 5 had proximal RCA stenoses. The mean age of the patients (35 men and 14 women) was 61 years, and their median New York Heart Association anginal class was III. The mean left ventricular ejection fraction was 42%. Femoral cardiopulmonary bypass support was used in 9 (19%) of 46 patients successfully managed with the keyhole procedure. Short-acting β-blockade was used in the majority of patients (38 of 46) to reduce heart rate and the vigor of cardiac contraction.

Results
All 49 patients have survived operation, which averaged 248 minutes in duration. Median postoperative endotracheal intubation time for keyhole patients was 6 hours with 25 of 46 patients being extubated before leaving the operating room. The median hospital stay was 4.3 days. Conversion to sternotomy was required in three patients to accomplish bypass because of inadequate internal mammary conduits[2] or acute cardiovascular decompensation during an attempted off-bypass keyhole procedure.[1] Postoperative complications were limited to respiratory difficulty in three patients and the development of a deep wound infection in one patient. Nine (19%) of 46 patients received postoperative transfusion. There have been no intraoperative or

postoperative infarctions, and angina has been controlled in all but one patients who subsequently had an IMA–RCA anastomotic stenosis managed successfully with percutaneous transluminal coronary angioplasty.

Conclusions

These early results with keyhole CABG are encouraging. As experience broadens, keyhole CABG may become a reasonable alternative to repeated endovascular interventions or sternotomy approaches to recalcitrant single-vessel coronary arterial disease involving the proximal LAD or RCA.

Coronary arterial bypass surgery has been shown to be an effective means of managing significant myocardial ischemia related to single-vessel coronary artery.[1-7] Because of the possible morbidity related to the sternotomy approach and the potential complications associated with cardiopulmonary bypass, operation has not been prescribed routinely as the first approach to this coronary artery disease pattern. Instead, endovascular coronary arterial interventions by percutaneous angioplasty techniques have been used, although the need for reintervention through repeat angioplasty or surgical revascularization may be required in up to 60% of patients.[8-11] This need for coronary reintervention has been shown to result in a greater overall treatment expense compared to an approach of initial surgical coronary revascularization. We and other surgical investigators have been exploring the utility of minimally invasive "keyhole" thoracotomy approaches to single-vessel coronary artery bypass as an alternative to catheter-related or classic transsternal surgical approaches to coronary revascularization.[12-16] This article describes our extended experience with the keyhole thoracotomy approach to coronary arterial revascularization. We also describe the indications for the selective use of thoracoscopic internal mammary arterial dissection and cardiopulmonary bypass support during the performance of this minimally invasive approach to coronary arterial revascularization.

MATERIALS AND METHODS

Forty-nine patients with a mean New York Heart Association angina class of III identified with single-vessel coronary artery disease involving the proximal left anterior descending coronary artery in 44 patients and the proximal right coronary artery (RCA) in 5 patients who were thought to be candidates for elective coronary artery revascularization were managed with the keyhole coronary artery bypass grafting (CABG) approach.[12-15] The median age of these patients was 63 years. Fourteen (28%) of the patients were women. Previous coronary interventions were common among these patients. Twenty-two had undergone previous attempts at percutaneous transluminal angioplasty of the "target" vascular lesion. Nine patients (19%) had an earlier coronary artery bypass procedure with either graft failure or progression of disease in the left anterior descending (LAD) or RCA requiring repeat surgical intervention. For the remaining 18 patients, this was their first coronary artery revascularization procedure. The average preoperative left ventricular ejection fraction for the group was 42%.

Subtotal or total occlusion of the LAD or RCA was the offending lesion requiring bypass in 40 patients. Obstructions of greater than 70% of the luminal diameter was present in the remaining nine patients.

Operative Technique

Anesthetic management similar to that used for standard cardiac surgery is used with diazepam premedication, propofol and fentanyl anesthetic induction and maintenance during the procedure with desflurane. Swan–Ganz pulmonary arterial catheterization and transesophageal echocardiography is used to monitor hemodynamics and ventricular wall motion. Double-lumen endotracheal tube intubation is established to facilitate visualization during the dissection of the internal mammary artery (IMA) pedicle. External defibrillator pads are positioned on the patient's chest away from the operative field, and these are connected to a cardioverter–defibrillator. Cardiopulmonary bypass pump support and perfusionists are available on "standby" status.

The patient is positioned in either a right or left 30-degree lateral decubitus position depending on the coronary artery being approached for bypass. The operative field extends across the thoracic midline to enable conversion to sternotomy if necessary. The ipsilateral groin and leg also are surgically prepared for possible femoral

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Address reprint requests to Rodney J. Landreneau, M.D., Allegheny General Hospital, Suite 302, 490 East North Avenue, Pittsburgh, PA 15212.

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arterial–venous access to cardiopulmonary bypass support and for possible saphenous vein harvest. Femoral arterial and venous catheterization are established to expedite access for cardiopulmonary bypass should this be necessary.

A 6-cm fourth interspace minithoracotomy then is performed along the inframammary crease.[14] The incision begins a few centimeters lateral to the sternal margin. The lower fibers of the pectoralis major muscle are divided, exposing the fourth costal cartilage. The perichondrium is incised, and a periosteal elevator then is used to free the cartilage. The cartilage is sharply separated from the rib laterally and disarticulated from its sternal connection. The posterior aspect of the perichondrium then is sharply incised to expose the underlying mammary pedicle. Local freeing of the pedicle then is performed using standard medial and lateral dissection techniques. The IMA is inspected to ensure its quality as a bypass conduit, and pedicle dissection is begun with ligation and division of segmental vascular branches of the mammary pedicle with small hemoclips and standard scissors. The endothoracic fascia is incised medially and laterally to the vascular pedicle as the dissection progresses. This "direct" dissection is extended beneath the fifth costal cartilage for a short distance and proximally beneath the third rib to the level of the second interspace with little difficulty.

We then choose to interrupt the mammary dissection at this point to open the pericardium and inspect the target zone of the coronary artery to be bypassed. A vertical incision in the pericardium is made, and traction sutures along the pericardial margins are applied to expose the target vessel. Unfavorable local conditions such as extensive vascular calcification, deep intramyocardial location, or small vessel size would lead us to convert to a standard sternotomy approach with cardiopulmonary bypass support to attempt the coronary revascularization. Localization of the target vessel requires a combination of careful mental review of the angiographic findings and familiarity with the regional anatomy, which can be visualized through this limited access approach. The left anterior descending artery will be encountered in a more lateral position through this incision among patients with ventricular hypertrophy. This should lead the surgical team to create the pericardiotomy in a slightly more lateral position. Conversely, when the proximal RCA is approached, it is important to establish the pericardial access close to the sternal margin to have optimal exposure of the acute margin of the heart.

Further dissection of the mammary artery pedicle was accomplished using direct dissection through the minithoracotomy in 27 patients and with "thoracoscopic assistance" in 22 patients. The direct dissection technique is performed using an upper-hand retractor to elevate the third rib to open the direct exposure of the parasternal space. On occasion, the third costal cartilage is incised to open the direct access to the mammary pedicle.[13,14] The cartilage margins are reapproximated with nonabsorbable monofilament heavy sutures at the time of wound closure. The direct dissection of the proximal mammary pedicle then is accomplished with standard instrumentation and techniques of vascular control with hemoclips and electrocautery. The upper aspects of the mammary pedicle usually can be freed using these direct dissection techniques; however, some patients with "long" sternal length are not completely accessible through this direct approach.

"Thoracoscopic-assisted" dissection of the upper aspect of the mammary pedicle is carried out by establishing initial intercostal access in the fourth intercostal space in the posterior axillary line.[14,16] As opposed to our description of the mammary dissection in an earlier report,[14] we now hold off on the thoracoscopic dissection until the lower aspect of the mammary pedicle is accomplished. This is because instrument access and thoracoscopic visibility to the lower reaches of the mammary pedicle naturally are impaired because of the anatomic relation of the lower sternum and heart. After accomplishing the lower dissection, a standard 10-mm 0-degree thoracoscope is used for videoscopic visualization of the pedicle dissection. Additional access sites are established in the third and fifth interspaces in the midaxillary line for endoscopic scissors, graspers, and vascular clip appliers. Standard dissection and vascular control techniques are used with this instrumentation under thoracoscopic camera vision relayed to television monitors.[17,18]

The mammary pedicle dissection is considered complete after division of the thymic branches and the large first intercostal arterial–venous connection is accomplished and the endothoracic fascia medial and lateral to the pedicle is free. Care is taken to avoid injury to the phrenic nerve during the upper aspects of the dissection. The endothoracic fascia then is incised at several levels along the pedicle to increase the length of the mammary arterial "reach" during the anastomotic procedure. Once this mammary dissection is completed, attention then is directed again to the cardiac aspects of the operation.

Preparation for internal mammary anastomosis to the target coronary artery is begun by re-establishing traction on the pericardial stay sutures, facilitating exposure of the coronary vessel. Further epicardial dissection about the coronary vessel is performed to gain enough vascular exposure for proximal and distal control and for the performance of the vascular anastomosis. Proximal and distal vascular control of the target coronary artery is accomplished at this point by looping silastic sutures

(Quest Medical, Inc., Dallas, TX) or similarly placed 5–0 polypropylene pledgeted sutures about the vessel.[13–16] One hundred milligrams of lidocaine and 10,000 U heparin then are administered intravenously. Test occlusion of the coronary artery then is performed. Transesophageal echocardiography is used to assess ventricular function. This arterial occlusion is performed to determine the possible need for femoral cardiopulmonary bypass support and to induce ischemic myocardial preconditioning.[19] This vascular occlusion is maintained, if tolerated, for 5 minutes, and then it is followed by an equal period of reperfusion before the ultimate vascular control used to accomplish the coronary anastomosis. The previously dissected IMA then is divided distally and prepared for suturing. Although patients with totally occluded coronary vessels routinely will tolerate this coronary occlusion without difficulty, our experience is that this test occlusion is most important for subtotal coronary obstructions. If significant myocardial dysfunction is noted shortly after coronary occlusion, femoral cardiopulmonary bypass is established after fully anticoagulating the patient. We then repeat the 10-minute cycle of ischemic conditioning–reperfusion before opening the coronary vessel. If there is no improvement in ventricular function as determined by transesophageal echocardiography, conversion to a sternotomy approach with standard cardioplegic arrest of the heart for coronary artery bypass is performed.

Once these maneuvers are completed and off-bypass keyhole coronary bypass is decided on, an osmolal or diltiazem infusion is begun and titrated to reduce the patients' heart rate to approximately 60 beats per minute. The vigor of myocardial contraction also is reduced by these medications.[20] Tension on the coronary artery snares then is applied, and the coronary artery is opened appropriately for anastomosis. An anastomosis between the IMA and the coronary artery then is accomplished using 7–0 or 8–0 polypropylene suture.[13–15] Any back bleeding from the coronary artery that can obscure the visibility of the vessel is managed by blowing a jet of carbon dioxide gas upon the vessel *via* a small suctioning device. Frequent saline irrigation or suctioning about the open coronary artery also can be used to facilitate an accurate anastomotic technique on the "beating heart." After the anastomosis is completed and hemostasis ensured, the osmolal–diltiazem infusion is discontinued. The anastomosis then is checked for patency with ultrasonic Doppler analysis of IMA flow. Cardiac pacing wires are not used routinely. The patient is weaned from cardiopulmonary bypass when it is used, and the femoral vessels then are repaired. The systemic heparinization is reversed with protamine after removal of bypass cannulas. A single 28-French chest tube is introduced through an available intercostal access site, and underwater seal drainage with 20 cm of negative pressure suction is established after closure of the keyhole thoracotomy.

Rapid reversal of the anesthetic is accomplished with an aim for early extubation. The patient then is transferred to the intensive care unit for standard postoperative monitoring and management. The chest tube is removed by the second postoperative day, and the patient usually is ready for discharge by the third or fourth postoperative day.

RESULTS

Forty-six (94%) of the 49 patients undergoing this keyhole technique of mammary arterial pedicle dissection and target coronary artery exposure had their coronary anastomosis successfully accomplished through this approach. Three patients required conversion to sternotomy to accomplish the coronary bypass procedure using standard aortic arch access for cardiopulmonary bypass and cardioplegic arrest. Two of these patients had inadequate internal mammary conduits for bypass and, thus, aortico-coronary saphenous vein grafting was used. Acute hemodynamic instability developed in the third patient while preparing for an off-bypass anastomosis and immediate conversion to median sternotomy was chosen to perform the internal mammary to coronary artery bypass procedure.

There have been no deaths or perioperative myocardial infarctions among any of the 49 patients approached with the keyhole procedure. Internal mammary artery pedicle dissection was successful without vessel injury in all patients. Nine patients underwent femoral cardiopulmonary bypass to support the circulation during the anastomosis. The period of bypass support averaged 70 minutes in duration. All anastomoses were performed on a beating heart that was slowed pharmacologically using the agents mentioned earlier in most cases. The average time required for internal mammary pedicle dissection using the direct approach was 49 minutes, which was similar to the 51 minutes needed for dissection when the thoracoscopic approach was used to dissect the upper mammary pedicle. Anastomotic time averaged 17.5 minutes. Internal mammary flow was substantiated in all of the 46 patients undergoing anastomosis, usually with ultrasound Doppler flow assessment. Intraoperative echocardiographic assessment of left ventricular anterior wall contractility and wall motion usually was noted to become mildly depressed during the conduct of the anastomosis. This ventricular dysfunction was reversed universally after the resumption of coronary flow after completion of the internal mammary anastomosis to the coronary artery. Total intraoperative blood loss averaged

178 ml, and 9 of the 49 patients required a postoperative blood product transfusion. Total operative time averaged 248 minutes. The mean intubation time after surgery was 6.1 hours with 21 patients (43%) undergoing successful extubation in the operating room. Postoperative complications were uncommon. Postoperative pneumonia developed in three patients, who required respiratory support and antibiotic therapy. Only one of these patients required reintubation and mechanical ventilator support. A deep thoracotomy wound infection developed in one final patient, a diabetic woman, who required local therapy and antibiotics. The mean hospital stay was 4.3 days. Although the length of follow-up is limited, only one patient has had clinical evidence of persistent myocardial ischemia after this keyhole approach to single-vessel coronary bypass surgery. This occurred in an obese, diabetic woman undergoing proximal internal mammary anastomosis to the RCA. A coronary angiogram obtained 6 weeks after surgery showed an anastomotic stenosis, which was managed successfully with percutaneous transluminal coronary angioplasty.

DISCUSSION

The primary defining characteristic of the keyhole coronary artery bypass procedure is the minimal thoracotomy access used to accomplish mammary artery pedicle dissection and the conduct of the internal mammary to coronary artery anastomosis. The performance of the coronary anastomosis on the beating heart without cardiopulmonary bypass support used in most instances must be considered a secondary feature of this procedure. As such, we must note that the performance of off-bypass single-vessel coronary artery bypass with internal mammary or saphenous vein conduits is not a new concept. In fact, the earliest pioneers in coronary artery bypass surgery used this approach before effective cardiopulmonary bypass circuitry was developed.[1-6,21] Our experience shows that this surgical approach to coronary artery revascularization is safe and effective management of single-vessel coronary artery disease involving the proximal LAD or RCA. Approach to the obtuse marginal system of the circumflex coronary artery and the posterior descending coronary artery are not achievable through this keyhole technique. The short- and intermediate-term effectiveness of this method of surgical coronary bypass grafting has been gratifying; however, longer term follow-up of these patients will be necessary to determine the true effectiveness of this approach.

We must ask ourselves the question, "What are the potential advantages and disadvantages of this approach?". As mentioned earlier, the long-term effectiveness of standard surgical bypass of coronary artery stenoses using the IMA has been shown to be far superior to catheter-related interventions.[1-6] The possibility of using a minimally invasive surgical approach to IMA bypass, which avoids the morbidity of sternotomy and cardiopulmonary bypass, therefore has obvious appeal.[13-16] We must state that the technical aspects of this surgery can be demanding and that a significant learning curve may be necessary before the surgeon develops comfort with this approach. A potentially negative tradeoff associated with this minimally invasive approach relates to the possibility of wasting the benefits of accurately performed IMA grafting to the coronary artery under the ideal conditions of sternotomy and cardioplegic arrest due to technical misadventure. Longer term results with this keyhole procedure will be necessary to define the relative risk and benefits of attempting this approach in lieu of sternotomy approaches to CABG.

The majority of these keyhole procedures currently can be accomplished using the direct dissection approach without the need for thoracoscopic manipulation. This fact has obvious appeal to the cardiac surgeon who has had little interest in video-assisted surgical techniques up until this point. However, there are patients with long chest configurations upon whom a complete dissection of the mammary pedicle will not be able to be accomplished using present methods of direct dissection through a single interspace keyhole thoracotomy. Certainly, one must question the true, minimally invasive nature of the direct dissection approach when several costal cartilages are divided or removed to completely dissect the mammary pedicle and provide adequate exposure of the heart for the bypass procedure. When faced with these circumstances during the mammary arterial pedicle dissection, we continue to believe that the thoracoscopic approach to the proximal IMA is useful.[14] Furthermore, we believe that truly video-assisted intercostal access only, coronary artery bypass surgery will be a reality in the not-too-distant future. Accordingly, facility with these video-assisted surgical techniques ultimately will benefit the cardiac surgeon in the long run.[16]

The avoidance of cardiopulmonary bypass is another potential advantage of this keyhole CABG approach. Although some would argue that the risk of cardiopulmonary bypass is minimal with present technology,[22] it is well established that postoperative pulmonary dysfunction, renal insufficiency, and neurologic impairment can be associated with the use of extracorporeal circulation during CABG.[23-26] Although the postoperative occurrence of these problems after cardiopulmonary bypass often is unpredictable, known preoperative dysfunction in these organ systems often will be made worse when the patient is subjected to cardiopulmonary bypass. These

potential complications and the risk of atheroembolism are even more prominent in the setting of reoperative CABG performed using cardiopulmonary bypass. Others also have reported that off-bypass CABG may be the preferred means of revascularization for ischemia in the LAD and RCA distribution among patients with impaired ventricular function and patients requiring surgery for postinfarction ischemic symptoms.[27]

We must, however, remember that there can be significant differences in the tolerance to local occlusion of a coronary vessel during the time of coronary anastomosis. We have uniformly been able to accomplish local vascular control and coronary anastomosis on the beating heart without precipitation of acute ventricular dysfunction; however, the clinical scenario can be quite different when the vessel stenosis is of a lesser degree. Varying degrees of ventricular dysfunction are noted routinely during the period of vascular anastomosis. Although "ischemic preconditioning" can assist in extending the tolerance to the ischemic event, there is certainly less margin for error when conducting an off-bypass coronary anastomosis upon less than critically stenosed coronary arteries. We have learned from percutaneous angioplasty techniques and results that periods of ischemia of several minutes during the dilation can be tolerated by the majority of patients as long as the ischemia ultimately is reversible. When a coronary anastomosis is imperfect and requires revision or if the performance of the anastomosis requires an inordinate length of time in this setting, an acute ventricular decompensation may occur. This has led us to be much more likely to have the femoral arterial and venous access for cardiopulmonary bypass ready when attempting off-bypass keyhole CABG in patients with less than critical coronary stenoses.

Keyhole coronary artery bypasses grafting is an exciting new development in the management of single-vessel coronary artery disease involving the LAD or proximal RCA. Bilateral sequential applications of this technique using the same anesthesia may allow for multivessel bypass of anteriorly located coronary stenoses. The primary limitation of this approach and for open off-bypass techniques for coronary revascularization relates to the inability to manage disease reliably in the obtuse marginal or distal RCA distribution. Refinements in minimally invasive approaches to cardioplegia delivery and cardiopulmonary bypass may assist us in expanding the role of such keyhole procedures aimed at total revascularization of the ischemic myocardium when multivessel coronary disease is present. The minimally invasive direct and thoracoscopic-assisted approaches represent a good intermediate step in the pursuit of totally endoscopic cardiac surgery.

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Discussion

DR. WILLIAM A. BAUMGARTNER (Baltimore, Maryland): That was a very nice presentation on a novel approach to this problem. As you know, our group has been interested clinically in the beating heart approach as well as in the laboratory investigating peripheral bypass and cardiac arrest to do this operation similar to the conventional approach.

One of the things that I think is key to this, and probably the most important aspect, is what you pointed out in the very beginning of your presentation, and that is at 18 years, will the patency of the left internal mammary artery be 80% to 90%. Based on experience other than that of the Brazilian surgeon, there has been a lot of data gathered on doing coronary artery bypass grafting (CABG) without cardiopulmonary bypass through a median sternotomy. Those have not been associated with particularly good results. Dr. Gundry previously reported poor results in patency after a beating heart approach.

I wonder, in your series, although you only have one patient who had a problem with a right coronary artery anastomosis, have you done any studies, either Doppler or angiogram, to confirm patency? The proof of this procedure is whether or not one has long-term patency.

I would also question whether or not it should be used in combination with percutaneous transluminal coronary angioplasty (PTCA). I think we have learned over the years that complete myocardial revascularization is really what should be strived for, and a combination of this with PTCA seems to be something that is against what we have learned over the years. I do think, though, that this is a novel approach and that it will find an appropriate place.

DR. ALDEN H. HARKEN (Denver, Colorado): I am interested in the gold standards that were so nicely developed in which both the Cass and European trials indicated that a mammary artery to the left anterior descending (LAD) or vascular arterial conduit to the LAD can be expected to last 10, perhaps even 20 years, with a 90% patency, while a PTCA from the Emory Angioplasty Surgery Trial is probably in the 60% patency at 6 months range.

Therefore, we are being challenged, I think, not only to evaluate the physiologic, financial, and functional costs of therapy, but also the physiologic, financial, and functional costs of remaining well after therapy. In that regard, surgical therapy or arterial grafts really look very, very good. So what we are discussing now is the psychology of clinical pathway development. What we therefore need to know is, what are the costs of not only the therapy but also the costs of remaining well after the therapy?

We are comparing a sternotomy *versus* a thoracotomy and femoral incision *versus* a PTCA or catheterization, and we have looked at the upper abdominal thoracotomy group *versus* a sternotomy, and a sternotomy surprisingly does not seem to hurt the vital capacity or exercise tolerance very much. Dr. Landreneau, have you looked at an FEV_1 or vital capacity or exercise tolerance at 1 day, 3 days, 3 weeks, and 3 months after therapy, because my sense is the durability of the surgical arterial graft is going to look very good in that regard.

My final question is actually not to Dr. Landreneau but to Dr. Sabiston. Could you possibly have imagined that this is what would have happened to the revascularization procedure that you developed reasonably recently?

DR. BRUCE A. REITZ (Stanford, California): I would like to congratulate Dr. Landreneau and his colleagues on this outstanding work and also, on a personal note, for his advice and encouragement in our early efforts in thoracoscopic mammary take-down.

I do believe these minimally invasive approaches to cardiac surgery are here to stay, and we will only see more and more development in the years to come. However, to be accepted, and for us to apply them widely, it needs to be shown that they are as safe and effective as our current operations. Certainly, the results that you present today are beginning to give us some security in that regard.

Certainly, they need to be pursued. The patients desire these approaches. They can see the benefits of minimally invasive surgery in the fields of general surgery, orthopedics, and gynecology. We also have the managed-care imperative requiring us to do more with less.

I wanted to just mention some work that has gone on for the last few years at Stanford. My colleagues and I have been working with an endovascular system that provides the type of cardiac arrest that we have with open surgery, to best apply minimally invasive techniques. To do this, a catheter-based system with femoral artery bypass, a balloon catheter positioned in the ascending aorta, and with assisted venous drainage was developed. There also is a retrograde coronary sinus catheter that can give cardioplegia in this manner if desired.

Using this catheter-based system, we have now used similar